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PENTAQUARKS - FACTS AND MYSTERIES
or SISYPHUS AT WORK

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ABSTRACT

Recent evidence for pentaquark baryons is critically reviewed in the light of new high statistics data. The search of the WA89 experiment for the $\Xi^{--}(1860)$ is presented in detail and consequences of its non-observations are discussed.

1 The Myth of Sisyphus

Giving these days a talk on pentaquarks or - even worse - writing afterwards a report for the proceedings reminds very much on Sisyphus, a man eternally condemned to roll a rock to the top of a mountain, whence the stone would fall back to its own weight. Having just finished the transparencies for the talk, the next paper with a new – positive or negative – result appears. In that sense, the present manuscript written during june 2004 represents an updated version of the talk given at the PANDA workshop in march 2004.

But may be there is even a deeper link between the pentaquark search and the destiny of Sisyphus. Since its advent in 1964 the quark model [1] is very much appreciated for describing the vast amount of strongly interacting particles, the so called hadron-zoo. Experimentally there is no doubt of the existence of baryons, made up of three quarks, and mesons, consisting of a quark anti-quark pair. A priori the quark model imposes no upper limit on the number of quarks/anti-quarks a hadron can be built of. However, it is widely agreed upon, that the colour quantum numbers of the constituents should add up to the colour neutral state. As a consequence physicist desperately seek for exotic quark and gluon structures which differ from the well known meson and baryon structure. Narrow resonances with exotic quark content would be of course particularly welcome because the theoretical interpretation would be very much simplified. In the past many new particles have been spotted like the tetra quark $U(3100)$ [2, 3], the $f_J(2230)$ seen first by the MARK III collaboration [4] and the $S(1936)$ [5]. Unfortunately none of these narrow resonances survived detailed studies with high statistics. So here we go again...

2 The Experimental Situation of the $\Theta^+(1530)$

At present twelve experimental groups have reported evidence for a narrow baryonic resonance in the KN channel at a mass of about 1530 MeV/c^2 (see Refs. 6-17) (for an updated list of references see [18]). Based on previous predictions [19] (for some earlier references see also [20]) this resonance was - because of its exotic quark content - interpreted as a pentaquark state. As a consequence already the first observations triggered a flood of theoretical papers which is still increasing with an increment of about one paper each second day (top part of Fig. 1).

Figure 2 shows the first nine published results which gave evidence for the existence of the so called $\Theta^+(1530)$. Unlike in the original publications I prefer to show here the data points including the statistical error bars. Obviously a common drawback of the individual observations is the limited statistics and hence limited confidence [21] of the peaks. A little bit disturbing is also the fact that the magnitude of the effect is nearly independent of the experimental situation. Because of the low statistics it is important to note that any cuts applied during the search process can modify the statistical significance of an a priori unknown peak unless the cuts are determined with an independent data

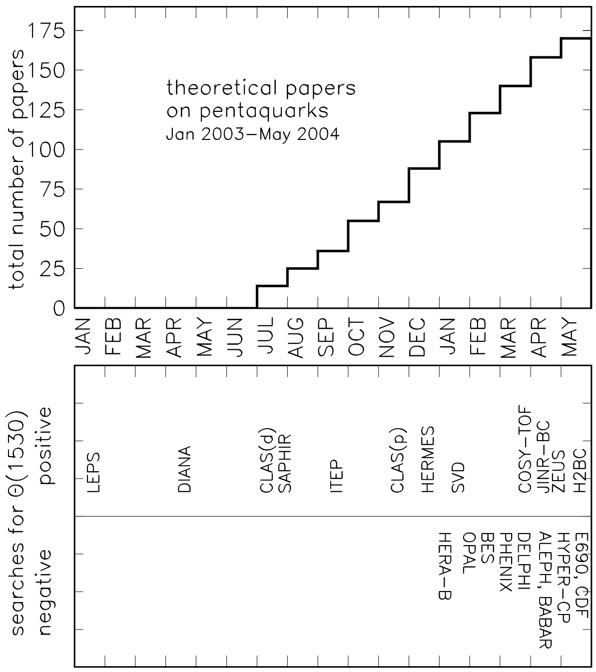


Figure 1: *Evolution of the total number of manuscripts discussing pentaquarks during the last months (top) and experiments reporting on the observation or non-observation of the* $\Theta^+(1530)$ *signal. Please note that some of the experimental results are displaced in this plot despite the fact that they have been presented nearly simultaneously.*

sample or Monte Carlo data (see e.g. [22]). The low statistics of the experiments shown in Fig. 2 did usually not allow to separate the data in two distinct data samples. It is furthermore interesting that the position of the various peaks are not fully consistent. Indeed already quite early doubts have been raised because of possible experimental artifacts [23, 24]. A recent analysis of the HYPER-CP collaboration also underlines the necessity to remove so called ghost tracks, i.e near-duplicate tracks, during the analysis [25]. Using the positive track from a Λ decay twice as a π^+ and a proton produces a peak near 1.54 GeV/c^2 (cf. also the discussion on Fig. 7 below). Finally, even if the observed peaks were real, more conventional processes can not be excluded completely at the

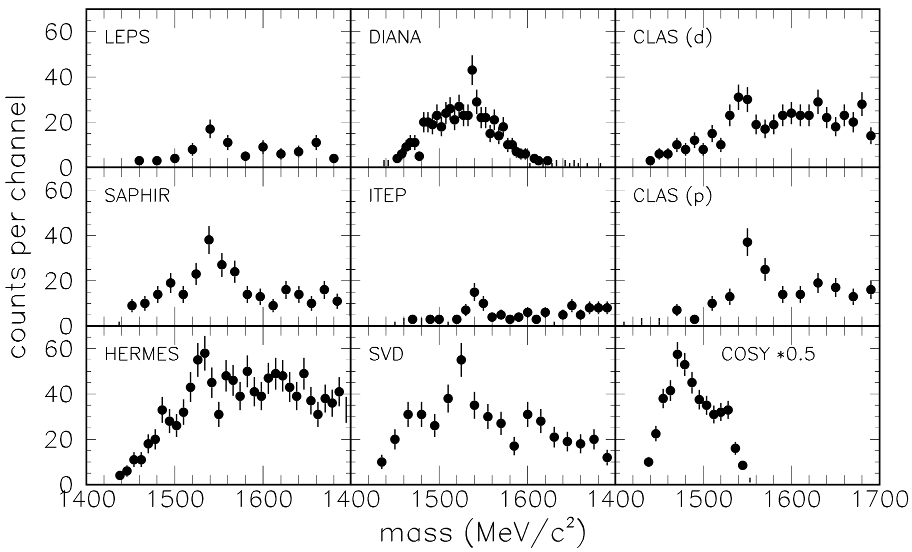
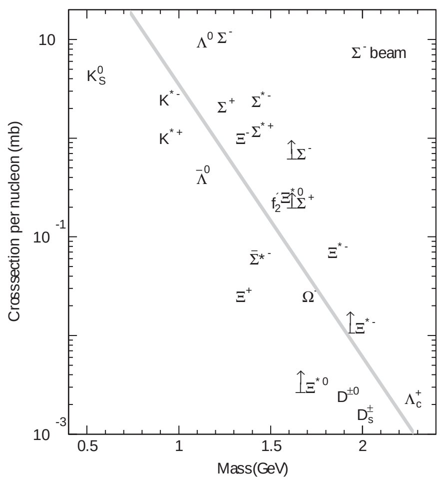


Figure 2: *Summary of the first nine published observations of the* $\Theta^+(1530)$ *resonance.*

moment [26, 27, 28, 29] (see however Ref. [30]).

Since the beginning of this year also quite a number of negative results became available (see lower part of Fig. 1). No signals of the $\Theta^+(1530)$ could be found by BES [31], HERA-B [32], OPAL [33], PHENIX [34], DELPHI [35], ALEPH [36], HYPER-CP [25], E690 [37], CDF [38] and BABAR [39]. Although a direct comparison of the positive and negative results is quite difficult, the discovery potential of the various experiment can be judged by the observed yield of known resonances. Whereas the experiments with a positive result have – if mentioned in the publications at all – typical $\Lambda(1520)$ yields of at most a few hundred, the experiments with negative outcome report in several cases a few thousand identified $\Lambda(1520)$ events. So while counting naively just the number of reported results, the situation is presently at near-balance (see Fig. 1), it seems that the critics have gained already an advantage. It is therefore indisputable that further high-statistics experiments are needed to establish the observed resonance beyond any doubt. Once this has been achieved – preliminary high statistics data of the LEPS collaboration seem



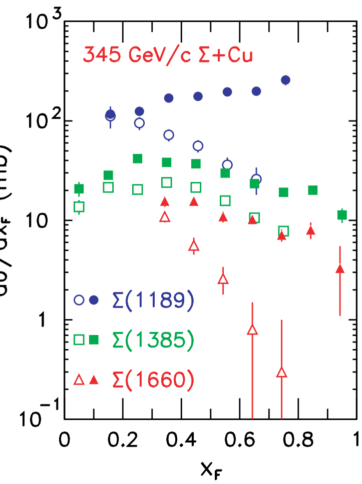


Figure 3: *Cross section per nucleon of various strange and charmed hadrons observed by WA89 in Σ^- reactions at 345* GeV/c.

Figure 4: x_F *distribution of positive (open symbols) and negative (closed symbols)* Σ *resonances studied by WA89.*

to confirm their first observation [40] – the observation and non-observation of these resonance in different reactions may help to shed some light on the production mechanism and possibly also on the internal structure of these exotic states.

3 The $\Xi(1860)$ - Another Stone for Sisyphus?

The interpretation of the observed peaks in terms of a five-quark state was significantly strengthened by the subsequent observation of another member of the anticipated antidecuplet of pentaquarks. Based on 1640 Ξ^- candidates produced in p+p interactions at 160 GeV/c beam momentum, both in the $\Xi^-\pi^+$ and the $\Xi^-\pi^-$ channels narrow peak structures at an invariant mass of 1.860 GeV/c^2 were observed by the NA49 collaboration [41]. Possible signals of a Ξ^* resonance at 1.860 GeV/c^2 decaying into $\Xi^-\pi^+$ and $Y\overline{K}$ were reported already 1977 for K$^-$p interactions at 2.87 GeV/c [42]. However, no corresponding signals have been seen in other K$^-$ induced reactions (for a compilation and a discussion of these data see Ref. [43]). A preliminary analysis of proton-nucleus

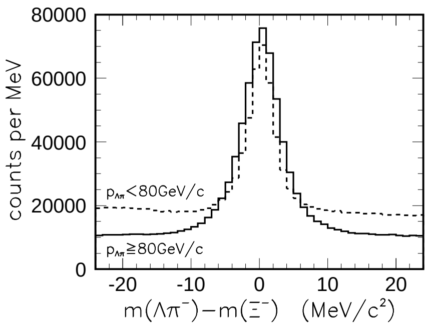


Figure 5: *Invariant mass distributions of* $\Lambda\pi^-$ *pairs with* $p_{\Lambda\pi} \geq$ *80* GeV/c *(solid histogram) and <80* GeV/c *(dashed histogram) in 340* GeV/c Σ^- *induced interactions.*

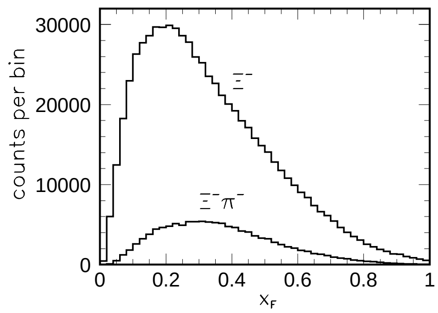


Figure 6: *Upper histogram:* x_F *distribution of the observed* Ξ^- *events within a* $\pm 2\sigma$ *mass window. Lower histogram:* x_F *distribution of the observed* $\Xi^-\pi^-$ *pairs within the mass range between 1.82 and 1.90* GeV/c^2*. In both cases the background has been subtracted by means of sideband events.*

interactions at 920 GeV/c by the HERA-B collaboration using a total of 19000 reconstructed Ξ^- and $\overline{\Xi}^+$ events, shows no indication for the Ξ^{--} nor the Θ^+ resonances [32]. Searches for the $\Xi(1860)$ resonances are also being performed by the ZEUS, CDF, ALEPH, E690 and the BABAR collaboration. The ZEUS data comprise 1361 Ξ^- and 1303 $\overline{\Xi}^+$ events, the CDF sample contains 19150 Ξ^- and 16736 $\overline{\Xi}^+$ and the ALEPH collaboration collected about 1800 Ξ^- . Negative – though still preliminary – results have been reported by all three collaborations at the DIS04 conference [44]. The E690 [37] and BABAR [45] experiments could not find a significant signal despite a large data sample of 512000 and 258000 observed Ξ^-, respectively. First preliminary results of the WA89 collaboration were presented at the HYP03 conference already in october 2003 [46]. The final result presented in the following section are available in Ref. [47]

4 The Hyperon Beam Experiment WA89

The hyperon beam experiment WA89 had the primary goal to study charmed particles and their decays. At the same time it collected a high statistics data sample of hyperons and hyperon resonances [48, 49, 50, 51, 52, 53, 54]. The hyperon beamline [55] selected Σ^- hyperons with a mean momentum of 340 GeV/c and a momentum spread of $\sigma(p)/p = 9\%$. In addition the beam contained small admixtures of K^- (2.1%) and Ξ^- (1.3%) [48]. The trajectories of incoming and outgoing particles were measured in silicon microstrip detectors upstream and downstream of the target. The experimental target itself consisted of one copper slab with a thickness of 0.025 λ_I in beam direction, followed by three carbon (diamond powder) slabs of 0.008 λ_I each, where λ_I is the interaction length. The momenta of the decay particles were measured in a magnetic spectrometer equipped with MWPCs and drift chambers. In order to allow hyperons and K^0_S emerging from the target to decay in front of the magnet the target was placed 13.6m upstream of the center of the spectrometer magnet.

The symbols in Fig. 3 mark the cross sections per nucleon for strange and charmed hadrons produced in Σ^- induced reactions at 345 GeV/c. In cases where the branching ratio of the observed decay channel is not known only lower limits are indicated by the vertical arrows. Typical for most hadronic interactions in this energy regime the cross sections follow roughly a mass dependence $\propto exp(-\Delta m/150MeV)$ as indicated by the straight line.

The importance of the projectile for the hyperon production is illustrated by the x_F distributions of positive (open symbols) and negative (closed symbols) Σ resonances shown in Fig. 4. Whereas at large x_F a significant enhancement of negative hyperons of nearly a factor of 10 is observed for the ground state, the decuplet resonance at 1385 MeV/c^2 shows an enhancement of less than 3. Considering the fact that for the $\Sigma^{\pm}_{1660}$ only values for $\sigma \cdot BR$ are given, the large cross section for Σ^-_{1660} seems particularly striking (see closed triangles in Fig. 4). Furthermore, the Σ^-_{1660} shows again an enhancement over the Σ^+_{1660} beyond a factor of 10. This is significantly larger than for Σ_{1385} but comparable to that of the ground state hyperons. Assuming that the observed Σ_{1660} is a $J^P = 1/2^+$ octet state, the strong leading effect for the Σ_{1660} as compared to the rather weak effect of the Σ_{1385} decuplet may be related to the $[ds]$ diquark structure. In the $J^P = 3/2^+$ decuplet hyperon the $[ds]$ diquarks

have spin 1, while in the Σ_{1660} the $[ds]$ diquarks have predominantly spin 0.

5 Search for the exotic $\Xi^{--}(1860)$ Resonance

Since statistics is the key point when looking for new particles, we also included interactions in the tracking detectors (silicon detectors and plastic scintillator) located close to these targets in our search for the S=-2 resonance in Σ^- induced reactions. Ξ^- were reconstructed in the decay chain $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$. The invariant mass distributions of the Ξ^- candidates are shown Fig. 5 for two regions of the total momentum of the $\Lambda\pi$ pair. The cut at 80 GeV/c corresponds to an x_F value of about 0.25 (see below). The WA89 analysis is based on a total of 676k Ξ^- candidates observed over a background of 170k $p\pi^-\pi^-$ combinations. Out of these candidates 240k, 281k and 155k can be attributed to the C, Cu and "Si+C+H" target, respectively.

Because of the strangeness content of the Σ^- beam also the cross sections for Ξ resonances are shifted towards large x_F with respect to the Σ^--nucleon cm-system [50]. Since in the WA89 setup the efficiency drops significantly at x_F <0.1 the yield of Ξ^- peaks at $x_F \approx 0.2$ (upper histogram in Fig. 6). $\Xi^-\pi^-$ pairs within the mass range of 1.82 to 1.90 GeV/c^2 are shifted to even larger x_F (lower histogram in Fig. 6). For comparison, the Ξ^- events observed by NA49 are distributed over an x_F range between -0.25 and +0.25 [56].

Fig. 7 shows the invariant mass spectrum of all observed $\Xi^-\pi^-$ pairs. Fig. 7b shows an extended view of the region around a mass of 1.862 GeV/c^2 marked by the arrows. All reactions, including also interactions in the tracking detectors close to the C and Cu targets, contribute to this figure. The structure observed at around 1.5 GeV/c^2 in the upper histogram of Fig. 7a is caused by events where the negative pion from the decay of the Ξ^- was wrongly reconstructed as a double track. As can be seen from the lower histogram in Fig. 7a, these fake pairs are reduced substantially by subtracting background from Ξ^- sideband events.

The NA49 collaboration has observed a ratio of Ξ^{--} to Ξ^- candidates of about 1/40. If we assume the same *relative* production cross sections over the full kinematic range for the reaction in question and similar *relative* detection efficiencies $[\varepsilon(\Xi^{--})/\varepsilon(\Xi^-)]_{WA89} \approx [\varepsilon(\Xi^{--})/\varepsilon(\Xi^-)]_{NA49}$ we would expect of the order of 17000 $\Xi^{--} \to \Xi^- + \pi^-$ events in our full data sample. The FWHM of the peaks observed by NA49 is 17 MeV/c^2 and is limited by the

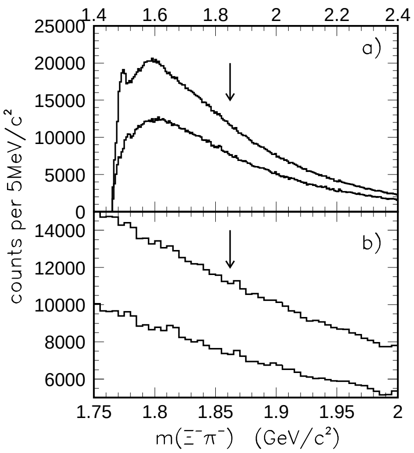


Figure 7: *Effective mass distribution of* $\Xi^-\pi^-$ *combinations of all reactions, including also reactions in the tracking detectors (Si+C+H) close to the C and Cu targets. Part b) shows an extended view of the region around 1.862* GeV/c^2 *marked by the arrows. Note the offset of the y-axis in this panel. In each panel the lower histogram shows the distribution after background subtraction via sidebands.*

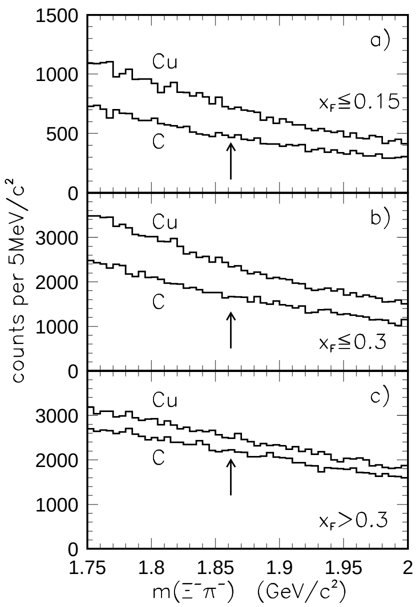


Figure 8: *Effective mass distribution of* $\Xi^-\pi^-$ *combinations with* $x_F(\Xi^-\pi^-)$ $\leq$*0.15 (part a),* $x_F(\Xi^-\pi^-)$ $\leq$*0.3 (part b) and* $x_F(\Xi^-\pi^-)$ $>$*0.3 (part c). In each plot the lower and upper histogram correspond to the carbon and copper target, respectively.*

experimental resolution. Since in our experiment the resolution is expected to be slightly smaller ≈ 10 MeV/c^2 (FWHM), this excess should be concentrated in less than 6 channels in Fig. 7b. Obviously, no such enhancement can be seen in the spectra.

The $\Xi(1860)$ events observed by NA49 are concentrated at small x_F. For a better comparison with the NA49 experiment we therefore scanned our data for different ranges of x_F. Fig. 8 shows the effective mass distributions of $\Xi^-\pi^-$ combinations with $x_F(\Xi^-\pi^-)$ $\leq$0.15, $\leq$0.3 and $>$0.3 in the region around 1.862 GeV/c^2. In each panel, the upper and lower histograms correspond to reactions with the carbon and copper target, respectively. No background

subtraction was applied to these spectra. Assuming again a Ξ^{--} to Ξ^- ratio of 1/40 as observed by NA49 and considering now only the x_F range between 0 and 0.15, we estimate that approximately 700 and 900 $\Xi^{--} \to \Xi^-\pi^-$ events should be seen in Fig. 8a for the C and Cu target, respectively. None of these spectra shows evidence for a statistically significant signal around 1.862 GeV/c^2, nor does such a signal appear in any other sub-sample.

Upper limits on the production cross sections were estimated separately for the copper and carbon targets, in five bins of x_F between $x_F = 0.15$ and $x_F = 0.9$. Assuming a dependence of the cross section on the mass number as $\sigma_{nucl} \propto \sigma_0 \cdot A^{2/3}$, where σ_0 is the cross section *per nucleon*, we obtained the limits on $BR \cdot d\sigma_0/dx_F$. Limits on the integrated production cross sections σ were then calculated by summing quadratically the contributions $d\sigma/dx_F \cdot \Delta x_F$ in the five individual x_F bins. The results are $BR \cdot \sigma_{max}(0.15 < x_F < 0.9)=$ 16 and 55 μb per nucleus in case of the carbon and copper target, respectively. An extrapolation to the cross sections per nucleon yields the two values $BR \cdot \sigma_{0,max} = 3.1\,\mu b$ for the carbon and $3.5\,\mu b$ for the copper target, in excellent agreement with each other. As can be seen from Fig. 3, these limits do not exceed the production cross sections of all other observed Ξ^* resonances.

At large x_F a significant fraction of the Ξ^- are produced by interactions induced by the Ξ^- beam contamination [48, 54]. Even if we were to assume that the $\Xi^{--}(1860)$ production can be attributed exclusively to the 1.3% Ξ^- admixture in the beam, we obtain e.g. for the carbon target and $x_F \geq 0.5$ a limit for the Ξ^{--} production by Ξ^- of 740μb. For comparison, even this large 3σ limit corresponds to only 4% of the Ξ^- production cross section in Ξ^-+Be interactions at 116 GeV/c in the same kinematic range [57].

Finally we note that the $\Xi^-\pi^+$ mass distribution observed in the 1993 data set by WA89 has already been published some years ago [49]. This combination is dominated by the peak from $\Xi^0(1530)$ decays (see Fig. 9). The observed central mass was in good agreement with the known value of M = 1531.8 $\pm$ 0.3 MeV/c^2 [58]. Unfolding the observed width with the width of the Ξ_{1530} of $\Gamma = 9.1$ MeV/c^2 [58] gave an experimental resolution of $\sigma_{\Xi^0(1530)}$ = 3.7 MeV/c^2. Furthermore, a weak resonance signal with a width of Γ = 10 ± 6 MeV/c^2 is visible at $M = 1686 \pm 4$ MeV/c^2 above a large background. In the mass region of the $\Xi^0(1860)$ no enhancement over the uncorrelated background can be seen in the WA89 data.

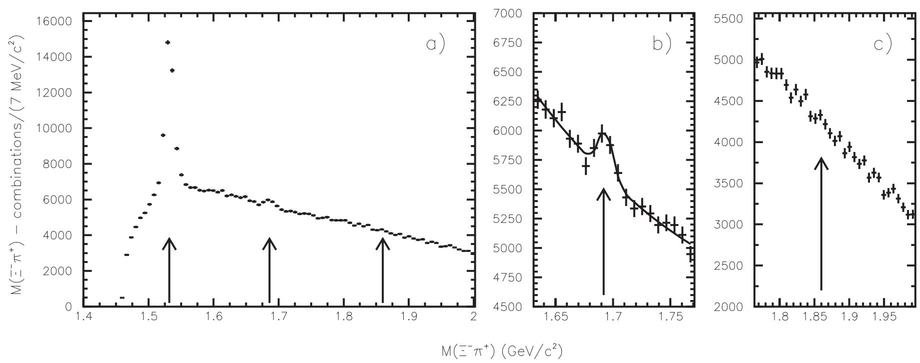


Figure 9: *Invariant mass distribution of the* $\Xi^-\pi^+$ *combinations published already six years ago* [49]*. a) the* $\Xi^0(1530)$ *and* $\Xi^0(1690)$ *mass region; b) the* $\Xi^0(1690)$ *mass region only; c) the mass region around 1860* MeV/c^2*.*

6 Quintessence

After an euphoric stage with many favorable reports within a short time we have now reached a phase which is much more unclear. Counting just the number of reported results the situation of the $\Theta^+(1530)$ is presently at most near-balance between sightings and non-sightings. It seems, however, that – because of the higher statistics – the non-sighting experiments gain the preponderance.

Considering the seven non-observations of the $\Xi^{--}(1860)$ resonance compared to the single claim in favor of it by the NA49 collaboration, this pentaquarks seems to stand of very shaky ground at present. *If*, nonetheless, the Ξ^{--} signal observed by the NA49 collaboration is real, then the non-observation in the WA89 experiment – as well as the other experiments – is not easily understood. Generally particle ratios do not vary significantly for the beam momentum range in question (160 GeV/c vs. 340 GeV/c) [59, 60]. The fact that the $\Theta^+(1530)$ has been seen in reactions on complex nuclei [11, 13] makes also the different targets (hydrogen vs. C, Si, Cu) an unlikely cause for the discrepancy. The internal structure of the Σ^- projectile or of the $\Xi^{--}(1860)$ could be a more plausible reason for the rather low limit of the $\Xi^{--}(1860)/\Xi^-$ ratio. It is well known, that a transfer of a strange quark from the beam projectile to the produced hadron enhances the production cross sections in particular at large x_F (see, for instance, Fig. 4). The different lead-

ing effects for octet and decuplet Σ states [51] even hint at an $[sd]$ diquark transfer from the Σ^- projectile [61]. The production of a pentaquark containing correlated quark-quark pairs (see e.g. Ref. [62]) would probably benefit from such a diquark transfer. However, for example in case of an extended $\overline{K} - N - \overline{K}$ molecular structure of the $\Xi(1860)$ [63] an $[sd]$ diquark transfer may not necessarily enhance the Ξ^{--} production leading also to a narrower x_F distribution. As a consequence the cross section in Σ^- induced reactions might not exceed the one for production in pp interactions. The latter cross section is predicted to be $\sim 4\mu$b [60] which is then close to our limit. Thus, if future high statistics experiments will confirm the production of the $\Xi^{--}(1860)$ resonance in proton-proton interaction, the non-observation with the Σ^- beam would point to a very exceptional production mechanism possibly related to an exotic structure of the $\Xi^{--}(1860)$. However, the possible non-observation by the E690 collaboration [37] in 800 GeV/c p-p interactions may even ruin this argument in favor of the $\Xi^{--}(1860)$ resonance.

Keeping in mind the past searches for exotic quark structures and looking at the present contradictory data, we can therefore not exclude that the stone of Sisyphus is just about to roll back downhill and that the quest for exotic pentaquark states may end where it began. May be QCD is indeed sticking to two and three valence quarks only and may be we are just lacking the right argument for this beautiful simplicity. In this situation it might be helpful to recall what Albert Camus said about the poor Sisyphus. Sisyphus *is* after all happy although he is fully aware that he will not succeed: *The struggle itself toward the heights is enough to fill a man's heart.*

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